QUADRUPOLE SEGMENTED ROD STUDY

N. Ierokomis
The Perkin-Elmer Corporation
Aerospace Division
2855 Metropolitan Place
Pomona, California 91767

April 1971
Interim Report for April 1971
Revised Final Submittal

Prepared for
GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland 20771

STANDARD TITLE PAGE

1. Report No	2. Government Accession No.	3. Recipient's Catalog No. 30001
4. Title and Subtitle QUADRUPOLE SEGMENTED ROD STUDY		5. Report Date April 1971
		6. Performing Organization Code
7. Author(s) N. Ierokomos		8. Performing Organization Report No.
9. Performing Organization Name and Address The Perkin-Elmer Corporation Aerospace Division 2855 Metropolitan Place Pomona, California 91767		10. Work Unit No.
		11. Contract or Grant No. NAS5-11185
12. Sponsoring Agency Name and Address Goddard Space Flight Center Greenbelt, Maryland 20771		13. Type of Report and Period Covered STUDY REPORT April 1971
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The sensitivity of the Quadrupole Mass Spectrometer is shown to have a strong dependence on the geometry of the entrance fringe fields. The longer an ion stays within a fringe field, which has both alternating current (ac) and direct current (dc) components, the larger its amplitude of motion; thus, the probability of being eliminated by the rods is higher. By use of parallel plate field geometry an ion experiences a side energy impulse which is proportional to the field strength. By combination of the two effects, achieving maximum ion transmission in a quadrupole is possible. This is physically accomplished by use of segmented rod geometry which only has an alternating current potential on the first rod segments. Considerable computer work was done to determine the ion trajectories in segmented rods. These results however, do not agree with the theoretical analysis of the published data.

17. Key Words (Selected by Author(s))	18. Distribution Statement		
19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
UNCLASSIFIED	UNCLASSIFIED	58	

PRECEDING PAGE BLANK NOT FILMED
ii, iii

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

INTRODUCTION

The introduction of ions into a quadrupole mass filter system inherently introduces affects which are detrimental to the probability of a stable ion traversing the length of the quadrupole without striking the rods. These conditions are determined by the characteristics of the stability of the system, fringing fields, phase, initial amplitude and entry angle, as well as several other parameters. Designing and operating a quadrupole in such a manner as to minimize one or several of the above detrimental characteristics is possible, for example, deceleration of the ions after they are accelerated to get the maximum intensity from the source and masking of ions having small values of amplitude which cause unstable particles to be very penetrating. In this report the use of segmented rods is discussed in the application of reducing the effects of the fringe fields and the instabilities of the scan line.

SCAN LINE EFFECT

A quadrupole operates as a mass filter by allowing only ions of a given mass-to-charge ratio (m/e) to be stable in traversing the rods while all other ions with different mass-to-charge ratios experience instabilities which cause these ions to continually increase their amplitude of motion until they impact the rods.

The stability of a given mass-to-charge ratio may be shown by the dimensionless quadrupole equations, slightly rearranged.

$$m/e = \frac{8\ Vdc}{a r_o^2 \omega^2} = \frac{4\ Vac}{q r_o^2 \omega^2} \qquad (1)$$

where: r_o = Center to rod distance

ω = Radio frequency (RF)

Vdc = dc potential at the rods

Vac = ac potential at the rods

Neglecting for a moment the variables a and q, Equation (1) immediately shows that if a quadrupole has a radius r_o from the center to the rod surface, it operates with a radio frequency

(RF) ω, and has a given direct current and alternating current potential at the rods, then there is only one mass-to-charge ratio that will satisfy this equation.

Since the value of r_0 is constant in a given quadrupole, to change the stability of a given mass-to-charge ratio, either the frequency of operation or the values of the direct current and alternating current potential at the rods may be changed. In changing the potentials the ratio of direct current to alternating current must be maintained as a constant, if all the successive mass-to-charge ratios are to have equal stability. This is because the variables a and q have a constant value for a given stability for all masses. For example, the apex of the first stability area of a quadrupole is at

$$a = 0.23699$$

$$q = 0.706$$

This is true for all masses. Rearranging equation (1), the ratio of potentials for the apex of the stability is obtained as

$$\frac{a}{q} = 2\,\frac{Vdc}{Vac} \tag{2}$$

which gives a ratio of 0.16784.

The above direct current to alternating current ratio determines the resolution of the system. This is because the region of operation within the a versus q graph (shown in Figure 1) will determine the stability of a given mass-to-charge ratio. If for example, the point of operation is such that the values of the direct current and alternating current potentials make the a and q values equal to those of the apex in the stability region, then the resolution of the system goes to infinity.

A quadrupole is normally scanned by varying the magnitude of the alternating current and direct current potentials along a scan line whose slope is determined by the resolution at which the system is to be operated. Figure 1 shows the typical a, q plot of the stability characteristics of a quadrupole with a scan line (SL) superimposed on this plot.

In Figure 1, two stability regions are shown to illustrate the point of one scan line being able to scan different masses (M and M') The scan line, as it develops from the origin to maximum transmission

$\left((a_1,q_o) \text{ or } (a_1',q_o')\right)$, passes through an unstable region first until it crosses the stability boundary for a given mass. The point of operation at the scan line, at any given time, can be simultaneously to the left of one mass-to-charge ratio stability region within the stability region of another (lower) mass-to-charge ratio and to the right of a still lower ratio. If the operation point is to the left of the stability region for a particular mass-to-charge ratio ion, then the motion of this ion is unstable in the Y-axis. If the point of operation is to the right side of the stability region, then the ion experiences an unstable X-axis motion. Any of these unstable mass-to-charge ratios will result in ions that will experience a continually growing amplitude of their motion as they traverse the rods.

The mass-to-charge ratios are unstable under two sets of conditions. The first is, that when the operating point along the scan line is within the stability region, very close to the apex of one mass-to-charge ratio, then all other ratios are unstable. The second set of conditions applies to all mass-to-charge ratios simultaneously, independent of the point of operation of the scan line. This is the area of the fringe fields which every ion must pass in entering the quadrupole rods. The geometry of the fringe fields can be determined by the physical entrance geometry of the quadrupole and the potential at the operating point. For simplicity, assume a quadrupole geometry that will cause the fringe field to follow the values of the direct current and alternating current potentials, with the same slope as the scan line. If this is accomplished then a stable mass-to-charge ratio ion, while in the fringe field region, will traverse along the scan line until it reaches the working point within the stability region. Until the ion reaches this working point, however, it has an unstable Y-axis motion because it is to the left of its stability region. This will cause the Y-axis amplitude to grow. The amplitude increases by an almost exponential growth and the rate of growth versus time spent in the unstable region is, of course, also determined by initial conditions such as the phase at which the ion enters with respect to the radio frequency field, initial amplitude and angle. The time an ion spends in the unstable region is largely dependent on the effective length of fringe fields which the ions must pass through before they are under the full strength of the alternating current and direct current fields.

Since the fringe fields can be defined by the scan line, then their relative affect can be calculated.

The average acceleration of an ion by the field can be expressed

$$\frac{d^2\bar{y}}{dt^2} = \ddot{\bar{y}} = 0.25\ (a - 0.4755q^2)\ \omega^2\ \bar{y} \qquad (3)$$

where

$\ddot{y}$ = acceleration averaged over several cycles

a and q are the dimensionless stability coordinates

ω = angle of oscillation f (frequency)

$\bar{y}$ = mean displacement

since at the apex

$$a = 0.4755\ q^2 \qquad (4)$$

$$\ddot{y} = 0.25\ \Delta a\omega^2\ \bar{y} \qquad (5)$$

The quantity 0.25 $\Delta a\omega^2$ can be considered as a spring constant for an undamped system.

If Δa is negative there is a restoring force. If Δa is positive the amplitude of an ion will continue to grow.

Since an ion found in the fringe field will most likely be found in the unstable region of Figure 1, the maximum radial acceleration (growing amplitude) can be compared with the restoring force of the stable region once the particle enters that region.

It was assumed that an ion in the fringe field travels along the scan line to the working point, then any

$$\frac{a_1}{q_1} = \frac{a_2}{q_2}$$

or

$$a_1 = \frac{a_2}{q_2}\ q_1 \qquad (6)$$

The scan line normally is very close to the apex so from Equation (4), a can be approximated

$$a_1 = \frac{1}{2} q_1^2 \tag{7}$$

then

$$\Delta a_1 = \frac{a_2}{q_2} q_1 - \frac{1}{2} q_1^2 \tag{8}$$

by differentiating Δa_1 with respect to q_1

$$\frac{d(\Delta a_1)}{dq_1} = \frac{a_2}{q_2} - q_1 = 0 \tag{9a}$$

or

$$q_1 = \frac{a_2}{q_2} \tag{9b}$$

substituting (9b) into (8)

$$\Delta a_1 = \left(\frac{a_2}{q_2}\right)^2 - \frac{1}{2}\left(\frac{a_2}{q_2}\right)^2 = \frac{1}{2}\left(\frac{a_2}{q_2}\right)^2 \tag{10a}$$

or, using the realtionship of Equation (6)

$$\Delta a_1 = \frac{1}{4} a_2 \tag{10b}$$

Since the scan line passes very close to the apex of the stability region for most resolving powers, Equation (7b) can be approximated as

$$\Delta a = \frac{1}{4} a_o = 0.059 \tag{11}$$

This value is positive, thus, it will cause the ion amplitude to grow continually. When this is compared to the restoring force inside the stability region note that it is of much higher magnitude for resolving powers higher than four (4), since

$$\frac{\Delta a}{a_o} = \frac{\Delta M}{M} \tag{12a}$$

where $\frac{\Delta M}{M}$ is the resolving power of the system

or

$$\Delta a = a_o \frac{\Delta M}{M} = \frac{1}{4} a_o \tag{12b}$$

then

$$\frac{\Delta M}{M} = \frac{1}{4} \tag{12c}$$

From the above analysis, the fringe fields appear to cause an ion to acquire a large amplitude proportional to the time it spends in this fringe region, as shown in Figure 2. Thus, elimination of fringe fields is desirable.

As an ion enters the quadrupole however, it will experience a side energy impulse which will be approximately proportional to the alternating current field strength for the first few cycles of the field before the ion can be normalized with the field. Since this impulse is proportional to the field strength over the first few cycles, a weak field is desirable to minimize the impulse.

To obtain a weak alternating current field strength and still maintain the correct working point a fringe field must be used.

Showing this impulse dependence on the fringe field in a quadrupole system mathematically is extremely difficult. However, analyzing a fringe field in a parallel plate configuration, which will give a result that approximates the results of a quadrupole field, is possible.

In a parallel plate geometry only ions with $\eta\pi$ phase to the field are stable while all other phases exhibit a constant drift term in their amplitude. In a quadrupole alternating current field all phases are stable but of different amplitude. In any event, parallel plate analysis will, in fact, give the relative magnitude of the drift rate of an ion in a varying field (fringe). Thus, if the drift rate is smaller in a long ramp field (field strength increasing slowly) it will indicate that long fringe fields impart a smaller impulse to the ions, which means improved operation of a quadrupole.

Let the field be defined by

$$E = (1 - e^{-\beta t}) E_o \sin (\omega t + \phi) \tag{13}$$

where

β = growth rate

t = time

E_o = field strength

ϕ = phase of ion entry

The differential equations of motion with respect to time are

$$\ddot{y} = \frac{q}{M} E_o (1 - e^{-\beta t}) \sin (\omega t + \phi) \tag{14}$$

integrating with respect to time

$$\dot{y} = \frac{q}{M} E_o \left[-\frac{1}{\omega} \cos (\omega t + \phi) - \frac{e^{-\beta t}}{\beta^2 + \omega^2} \left\{ -\beta \sin (\omega t + \phi) - \omega \cos (\omega t + \phi) \right\} \right] + C \tag{15}$$

solving for C at $t = 0$; $\dot{y} = \dot{y}_o$

$$C = \dot{y}_o - \frac{q}{M} E_o \left\{ -\frac{1}{\omega} \cos \phi + \frac{1}{\beta^2 + \omega^2} (\beta \sin \phi + \omega \cos \phi) \right\} \tag{16}$$

resulting in

$$\dot{y} = \frac{q}{M} E_o \left[-\frac{1}{\omega} \cos (\omega t + \phi) + \frac{e^{-\beta t}}{\beta^2 + \omega^2} \left\{ \beta \sin (\omega t + \phi) + \omega \cos (\omega t + \phi) \right\} \right] + \dot{y}_o - \frac{q}{M} E_o \left\{ -\frac{1}{\omega} \cos \phi + \frac{1}{\beta^2 + \omega^2} (\beta \sin \phi + \omega \cos \phi) \right\} \tag{17}$$

Integrating again with respect to time to obtain the amplitude y and solving for the second constant of integration:

$$y = \left[\dot{y}_o - \frac{q}{M} E_o \left\{ \frac{\beta \sin \phi + \omega \cos \phi}{\beta^2 + \omega^2} - \frac{\cos \phi}{\phi} \right\} \right] t$$

$$+ \frac{q}{M} E_o \left[- \frac{\sin(\omega t + \phi)}{\omega^2} - \frac{\beta e^{-\beta t}}{(\beta^2 + \omega^2)^2} (\beta \sin(\omega t + \phi) + \omega \cos \right.$$

$$\left. (\omega t + \phi) + \frac{\omega e^{-\beta t}}{(\beta^2 + \omega^2)^2} \left(- \beta \cos(\omega t + \phi) + \omega \sin(\omega t + \phi) \right) \right] +$$

$$y_o - \frac{q}{M} E_o \left[- \frac{\sin \phi}{\omega^2} - \frac{1}{(\beta^2 + \omega^2)^2} \right.$$

$$\left. (- \beta^2 \sin \phi - 2\beta\omega \cos \phi + \omega^2 \sin \phi) \right] \tag{18}$$

For the condition where $\beta \gg \omega$ (short ramp field strength increasing quickly)

$$y = y_o + \dot{y}_o t - \frac{q}{M} \frac{E_o}{\omega^2} \left[\sin(\omega t + \phi) - \sin \phi \right] - \frac{q}{M} \frac{E_o}{\beta} \left(\sin \phi + \right.$$

$$\left. 2 \frac{\omega}{\beta} \cos \phi \right) - \frac{q}{M} \frac{E_o}{\omega} \left(\frac{\omega}{\beta} \sin \phi - \cos \phi \right) t \tag{19}$$

The terms which have a growth rate are

$$\dot{y}_o t - \frac{q}{M} \frac{E_o}{\omega} \left(\frac{\omega}{\beta} \sin \phi - \cos \phi \right) t \qquad \beta \gg \omega \tag{20}$$

This has to be compared with the growth term with conditions of $\beta \ll \omega$ (long ramp)

$$y = y_o + \dot{y}_o t - \frac{q}{M} \frac{E_o}{\omega^2} \left[\sin(\omega t - \phi) - \sin \phi \right] + \frac{q}{M} \frac{E_o}{\omega^2}$$

$$\left(\sin \phi - 2 \frac{\beta}{\omega} \cos \phi \right) - \frac{q}{M} \frac{E_o}{\omega^2} \beta t \sin \phi \tag{21}$$

The growth terms from Equation (21) are

$$\dot{y}_o t - \left(\frac{q}{M} \frac{E_o}{\omega^2} \beta \sin \phi \right) t \qquad \beta \ll \omega \tag{22}$$

In order for the impulse to be small with long ramps

$$\frac{\dot{y}_o t - \frac{q}{M} E_o \left(\frac{1}{\beta} \sin \phi - \cos \phi\right) t}{\dot{y}_o t - \frac{q}{M} E_o \left(\frac{\beta}{\omega^2} \sin \phi\right) t} > |1| \tag{23}$$

To compare the oscilatory terms let

$$\dot{y}_o t - \frac{q}{M} E_o = K_1 - K_2 \tag{24}$$

then

$$\frac{K_1 - K_2 \left(\frac{1}{\beta} \sin \phi - \cos \phi\right) t \quad \beta >> \omega}{K_1 - K_2 \left(\frac{\beta}{\omega^2} \sin \phi\right) t \quad \beta << \omega} > |1| \tag{25a}$$

or

$$\frac{\frac{1}{\beta} \sin \phi - \cos \phi}{\frac{\beta}{\omega^2} \sin \phi} > |1| \tag{25b}$$

when $\quad \phi \rightarrow \eta\Pi; \ \frac{1}{\beta} \sin \phi - \cos \phi \rightarrow \pm 1$

and $\quad \frac{\beta}{\omega^2} \sin \phi \rightarrow 0$

thus; Equation (25) $\rightarrow \pm\infty$

when $\quad \phi \rightarrow \frac{\eta\Pi}{2}; \ \frac{1}{\beta} \sin \phi - \cos \phi \rightarrow \pm \frac{1}{\beta}$

and $\quad \frac{\beta}{\omega^2} \sin \phi \rightarrow \pm \frac{\beta}{\omega^2} < \frac{1}{\beta}$

Thus, the amplitude growth is shown to experience a smaller change due to the impulse from a long ramp field than a short one, see Figure 3. This is the desired end result in normal quadrupole operation where the initial entrance amplitude and side energy of an ion are small. If the initial amplitude and side energy are large. then under some phases the short ramp is more beneficial than a long ramp.

Considerable effort can be spent to determine the best ramp conditions for a quadrupole with known distribution of amplitudes and entrance side energies if operating a quadrupole at maximum efficiency is desired.

For a given set of entrance conditions there apparently will be only one ramp geometry that will provide optimum results. Shortening or lengthening the fringe field ramp will deteriorate the operation of the system.

Figures 2 and 3, which are the two contributions of amplitude for an ion in a fringe field, can be normalized and combined to determine the general shape of the ion amplitude with respect to the length of the fringe field with the results shown in Figure 4.

Figure 5 shows a typical field ramp or fringe field geometry to a working point at the scan line.

From Figure 4 note that with a normal scan line, which passes through the unstable region, fringe fields of about one to three cycles possess minimum amplitude. Fringe fields of longer duration exhibit a fast increase of amplitude due to the exponential growth of the term that is determined by the time the ion spends in the unstable region. A large amplitude is, of course, detrimental to the operation of the quadrupole because ions with such large amplitudes will hit the rods and be eliminated.

Figure 4 also indicates that the greater part of the ion amplitude is attributed to the time an ion spends within the unstable region. This time can be characterized by the field ramp (see Figure 5) of varying length. W.M. Brubaker[1] has shown by use of computer data that a ramp of two cycles gives a lower amplitude to ions than no ramp at all and is several hundred times lower than a ramp of ten cycles. These data confirm the general shape of Figure 4.

---

1 "A study of the Introduction of Ions into the Region of Strong Fields Within a Quadrupole Mass Spectrometer", W.M. Brubaker, 1967 Final Report, Contract NAS2-1298.

In a quadrupole keeping the ion amplitudes small is important to keep the ions from hitting the rods. The ion amplitudes can be greatly reduced if the scan line of the quadrupole fringe field can be altered so that it is found entirely within the stability region. Figure 6 shows a typical scan line versus a desired scan line of operation.

A scan line, as shown in Figure 6 (desired), is difficult to achieve and still scan many masses, but similar affect can be obtained by making the fringe fields mostly alternating current, delaying the direct current fringe. In this way, obtaining a long alternating current ramp which will impart small initial impulses to an ion as it enters the field is possible, while the absence of the direct current fringe field will allow all ions to be stable until the ions adjust to the alternating current field. The application of the delayed direct current will not begin to filter the ions of different mass until these ions are stabilized with respect to the radio frequency field.

This effect can be easily obtained, as Brubaker has shown, by use of segmented rods, where essentially there are two quadrupoles in tandem and the first four rods have only alternating current applied to them.

By use of this method, Brubaker has shown that the amplitude of ions in an alternating current delayed direct current ramp can be reduced to about one-third the magnitude of the best alternating current plus direct current ramp (of about two cycles).

Such a large reduction of amplitude of course means higher sensitivity of the quadrupole at a given resolution.

Additional segments however, make the quadrupole longer. Another approach to small amplitudes utilizes high energy ions and quadrupole bias. An ion with high energy quickly passes through the fringe field; thus, remaining in the unstable region for a very short time. The application of quadrupole bias slows the ions down so that these ions will spend sufficient time within the quadrupole to be adequately filtered.

The end result of high energy ions with quadrupole bias is to achieve a minimum amplitude of ions with minimum length and weight of the quadrupole. The amplitude of the ions in this approach is not considered much higher than a factor of two to three higher than that obtained with segmented rods, since the operating point is in the valley of the curve in Figure 4. Thus, the sensitivities of the two approaches may be considered comparable for small initial entrance angles and amplitudes.

COMPUTER ANALYSIS

All of the mathematical analysis of the fringe field ramps was done with fields of parallel plates and then the assumption was made that the results could be applied to quadrupole fields. Brubaker has performed considerable computer work of ion trajectories in segmented quadrupole fields, but it was felt that additional data was required to determine the optimum ramp characteristics for upper atmospheric research applications which could utilize segmented rod geometry.

The first approach undertaken was to determine the mathematics for a hyperbolic ramp and write a computer program to analyze ion trajectories in such fields. The results were of such complexity that it would have required considerable time and effort to obtain a final amplitude of the ions.

The most reasonable approach appeared to be one of utilizing our existing computer programs for ion trajectories in quadrupoles modified to contain a fringe field ramp, then use the identical initial conditions which Brubaker used and compare the end results with those of Brubaker.

To accomplish this, it was necessary to break the program into two subroutines. The first part was the ramp section, where the computer determined the trajectory of the ion with continually varying a and q parameters according to the field variations of the ramp. The computer would then determine the exit conditions of the ramp, such as amplitude, angle and phase, and use these conditions as the entry conditions for the second subroutine where the fields were constant.

The resultant amplitudes were compared with those given in Reference 1 at approximately the same number of cycles down the Z-axis and were found to be, in all cases, larger than those obtained by Brubaker. This was true for both Y and X axes.

As a further check, several phases were run and, also, a comparison was made with a no ramp condition. Again, the amplitude obtained with a ramp was higher than with no ramp. The data for both ramp and no ramp conditions is shown in Appendix A.

The results of this computer analysis indicated that there is perhaps some subtle error in the approach, taken here, in manipulating the ramp of the fields. Examining the computer program and method did not appear to shed any light on the matter.

SUMMARY

Theoretical analysis indicates that correct manipulation of the entrance fringe fields could be very beneficial in the operation of a quadrupole mass spectrometer. This manipulation can take the form of an alternating current delayed direct current ramp as in the segmented rod approach, or an alternating current plus direct current ramp as in the biasing of the quadrupole approach. Segmented rod geometry appears to give higher intensity for a given set of conditions, but quadrupole bias has an edge on length and weight conditions. The computer data obtained herein can only be termed inconclusive with considerably more effort required to correct and complete the approach and programs.

PRECEDING PAGE BLANK NOT FILMED

APPENDIX A

Computer Data for Various Conditions

1. Different Ramps
2. Different a and q Values
3. Different Phases
4. No Ramp

Figure 7 shows the relative maximum amplitudes of the ion trajectories computed herein.

APPENDIX A

ANALYSIS I

a = .2346200; q = .7048200
.2330000 .7060000

ac ramp 0° to 4320°

dc ramp 2160° to 4320°

$\gamma = 0$

$\eta = 0.010$

$\phi = 0°$

Also compared with no ramp condition

X - RODS RAMP #1

Segmented rod transmission analysis. Enter a and q, dc and ac ramp entrances, and exits. ?.23462, .70432,2160,.4320,4320,. Enter initial phase

?
A = .23462000 Q = 70482000

DC Ramp
Entrance = 2160 Exit = 4320
AC Ramp
Entrance = 0 Exit = 4320

X-Axis Analysis
Enter ETA and GAMMA
?.01,
X-ETA = .0100 X-GAMMA = .00000
Initial Phase = 0

PHASE	AMP	PHASE	AMP
134	.0100	1422	.0099
358	.0104	1649	.0075
530	.0100	1768	.0079
715	.0107	2897	-.0053
900	.0097	3068	-.0040
1070	.0107	3209	-.0048
1271	.0090	3949	.0053

Phase Distance = 4320 Phase Angle = 360 **Ramp exit conditions**
X-ETAF = -.0019 X-GAMMAF = -.00230

APPENDIX A

Y-RODS RAMP #2

Y-Axis Analysis
Enter ETA and GAMMA — A = .?346200
?.01, — Q = .7048200
Y-ETA = .0100 Y-GAMMA = .00000
Initial Phase = 0

PHASE	AMP
134	.0100
362	.0096
525	.0100
726	.0091
886	.0097
1093	.0084
1241	.0090
1467	.0071
1589	.0075
1867	.0048
1912	.0048
2769	-.0040
2802	-.0040
3084	-.0083
3204	-.0074
3438	-.0140
3568	-.0119
3798	-.0236
3925	-.0199
4159	-.0429
4282	-.0362

Phase Distance = 4320 Phase Angle = 360 Ramp exit conditions
Y-ETAF = -.0382 Y-GAMMAF = -.02092

APPENDIX A

X-RODS Second Segment #1A

Quadrupole Trajectory Maxima

Enter A, Q, ETA, GAMA, I PHASE, X and or Y
?.23462,.70482,-.00;9,-.0023,0,X

A = .23462000 Q = .70482000 GAMMA - -.00230

X-Axis Analysis

PHASE	AMP	PHASE	AMP		
0	-.0019	10077	-.0230		
51	-.0022	10438	.0268		
154	-.0019	10798	-.0302		
331	-.0034	11159	.0329		
709	.0084	11519	-.0351		
1073	-.0133	11979	.0366		
1435	.0180	12240	-.0373		
1797	-.0223	12600	.0374		
2157	.0262	12960	-.0368		
2518	-.0296	13321	.0355		
2879	.0325	13681	-.0335		
3239	-.0348	14042	.0309		
3599	.0364	14402	-.0277		
3960	-.0373	14763	.0239		
4320	.0375	15124	-.0198		
4680	-.0370	15486	.0152		
5041	.0358	15849	-.0104		
5401	-.0339	16001	-.0028	.0101	final
5762	.0314	16001	-.0028	.0101	conditions
6122	-.0282				
6483	.0246				
6844	-.0205				
7205	.0160				
7568	-.0112				
7935	.0063				
8617	-.0042				
8990	.0092				
9354	-.0141				
9716	.0187				

1600° = 44.4 Cycles = Length of Quadrupole
(for mass 50 with 10 ev energy)

APPENDIX A

Y-RODS Second Segment 2A

Quadrupole Trajectory Maxima
Enter A,Q,ETA,GAMA,I PHASE, X and/or Y
?.23462,.70482,-.0382,-.02092,,Y

A = .23462000 Q = .70482000 GAMA = -.02092

Y-AXIS Analysis

PHASE	AMP	PHASE	AMP	PHASE	AMP	
0	-.0382	6871	-.0290	14216	.1297	
186	-.0973	7004	-.0398	14416	.0541	
346	-.0584	7753	.0486	14573	.0887	
544	-.1378	7894	.0336	14787	.0324	
710	-.0784	8107	.0911	14926	.0461	
903	-.1756	8265	.0553	15675	-.0422	
1073	-.0967	8464	.1320	15811	-.0303	
1262	-.2098	8630	.0755	16001	-.0824	-.0373
1435	-.1130	8823	.1702	16001	-.0824	-.0373
1622	-.2399	8992	.0941			
17[illegible]	-.1270	9182	.2050			
1981	-.2651	9354	.1108			
2157	-.1385	9542	.2357			
2341	-.2850	9716	.1251			
2518	-.1471	9901	.2617			
2701	-.2992	10077	.1370			
2879	-.1528	10261	.2825			
3060	-.3074	10438	.1460			
3240	-.1553	10621	.2975			
3420	-.3095	10799	.1521			
3601	-.1548	10980	.3066			
3780	-.3052	11160	.1552			
3961	-.1511	11340	.3095			
4139	-.2949	11520	.1551			
4322	-.1444	11700	.3063			
4499	-.2787	11881	.1519			
4683	-.1348	12059	.2968			
4859	-.2568	12242	.1456			
5044	-.1224	12419	.2814			
5218	-.2298	12603	.1364			
5406	-.1075	12779	.2604			
5578	-.1982	12964	.1244			
5768	-.0905	13138	.2341			
5937	-.1626	13326	.1099			
6131	-.0715	13498	.2031			
6295	-.1238	13688	.0931			
6497	-.0510	13857	.1681			
6653	-.0825	14051	.0744			

Final conditions

APPENDIX A

X-RODS RAMP #3

Segmented Rod Transmission Analysis

```
A = .2330000  Q = .70600000
          DC RAMP
Entrance = 2160  Exit = 4320
          AC RAMP
Entrance = 0  Exit = 4320

X_AXIS Analysis
Enter ETA and GAMMA
?.01,,
X-ETA = .0100  X-GAMMA = .00000
Initial Phase = 0
```

PHASE	AMP
134	.0100
358	.0104
530	.0100
715	.0107
900	.0097
1070	.0107
1272	.0090
1422	.0099
1649	.0075
1768	.0079
2897	-.0053
3068	-.0040
3209	-.0048
3949	.0053

Phase Distance = 4320 Phase Angle = 360   **Ramp exit conditions**

X-ETAF = -.0019 X-GAMMAF = -.00230

APPENDIX A

```
Y-RODS RAMP #4

Y-AXIS Analysis                           A = .2330000
Enter ETA and GAMMA                       Q = .7060000
?.01,
Y-ETA = .0100  Y-GAMMA = .00000
Initial Phase = 0

PHASE          AMP

  134         .0100
  362         .0096
  525         .0100
  726         .0091
  886         .0097
 1093         .0084
 1241         .0090
 1467         .0070
 1589         .0075
 1868         .0048
 1912         .0048
 2767        -.0040
 2804        -.0040
 3084        -.0083
 3204        -.0074
 3438        -.0139
 3568        -.0118
 3797        -.0233
 3926        -.0196
 4158        -.0420
 4283        -.0353

Phase Distance = 4320  Phase Angle - 360     Ramp exit conditions

Y-ETAF = -.0371  Y-GAMMAF = -.02001

To enter quadrupole without ramp type GO
?GO
Enter quadrupole length.
Enter Inputs?
?16000,YES
```

APPENDIX A

X-RODS Second Segment 3A

Quadrupole Trajectory Maxima

```
Enter A,Q,ETA,GAMA,I PHASE, X and/or Y
?.233,.706,-.0019,-.0023,X+,X
```

A = .23300000 Q = .70600000 GAMMA = -.00230

X-AXIS Analysis

PHASE	AMP	
0	-.0019	
51	-.0022	
154	-.0019	
331	-.0034	
709	.0084	
1073	-.0134	
1435	.0180	
1797	-.0223	
2157	.0261	
2518	-.0295	
2879	.0322	
3239	-.0343	
3599	.0356	
3960	-.0363	
4320	.0362	
4681	-.0354	
5041	.0339	
5401	-.0317	
5762	.0288	
6123	-.0254	
6484	.0214	
6845	-.0170	
7207	.0123	
7573	-.0074	
7964	.0024	
8085	.0019	
8248	.0032	
8629	-.0082	
8993	.0131	
9355	-.0178	
9717	.0221	
10077	-.0260	
10438	.0293	
10799	-.0321	
11159	.0342	
11519	-.0356	
11880	.0363	
12240	-.0362	
12601	.0355	
12961	-.0340	
13321	.0318	
13682	-.0290	
14043	.0256	
14404	-.0216	
14765	.0173	
15127	-.0126	
15492	.0076	
15879	-.0027	
16001	-.0019	.0005
16001	-.0019	.0005

Final conditions

APPENDIX A

Y-RODS Second Segment 4A

Quadrupole Trajectory Maxima

Enter A,Q,ETA,GAMA,I PHASE, X and/or Y
?.233,.706,-.0371,-.02001,,Y

A = .23300000 Q = .70600000 GAMMA = -.02001

Y-AXIS Analysis

PHASE	AMP	PHASE	AMP	PHASE	AMP	
0	-.0371	5751	.0712	11517	-.0932	
186	-.0941	5942	.1570	11701	-.1923	
347	-.0558	6115	.0847	11879	-.0982	
544	-.1301	6301	.1796	12060	-.1974	
712	-.0727	6477	.0939	12241	-.0983	
902	-.1596	6661	.1932	12419	-.1927	
1075	-.0858	6939	.0984	12603	-.0935	
1261	-.1813	7020	.1974	12779	-.1785	
1437	-.0946	7201	.0980	12966	-.0840	
1621	-.1941	7379	.1917	13138	-.1555	
1799	-.0986	7563	.0928	13329	-.0703	
1980	-.1972	7738	.1766	13496	-.1248	
2161	-.0977	7926	.0828	13694	-.0529	
2339	-.1906	8097	.1528	13854	-.0880	
2524	-.0920	8289	.0687	14066	-.0325	
2698	-.1746	8456	.1214	14207	-.0470	
2886	-.0816	8655	.0510	14955	.0410	
3057	-.1500	8813	.0841	15091	.0295	
3250	-.0671	9028	.0304	15307	.0825	
3416	-.1180	9166	.0428	15465	.0502	
3616	-.0491	9914	-.0452	15664	.1200	
3773	-.0802	10053	-.0316	15831	.0680	
3991	-.0282	10267	-.0864	16001	.1485	.0554
4124	-.0386	10425	-.0521	16001	.1485	.0554
4862	.0494	10624	-.1234			
5015	.0338	10791	-.0696	Final conditions		
5226	.0903	10983	-.1544			
5386	.0540	11154	-.0835			
5584	.1268	11342	-.1777			

APPENDIX A

NO RAMP #5 (See #1 and 1A)

Quadrupole Trajectory Maxima

Enter A,Q,ETA,GAMA,I PHASE, X and/or Y
?.23462,.70482,.01,,0,XY

A = .23462000 Q = .70482000 GAMMA = .00000

X AXIS Analysis

PHASE	AMP		PHASE	AMP	
0	.0100		10082	-.0076	
360	-.0099		10443	.0066	
721	.0096		10704	-.0055	
1081	-.0092		11165	.0043	
1442	.0085		11528	-.0031	
1802	-.0077		11895	.0017	
2163	.0068		12325	-.0005	
2524	-.0057		12354	-.0005	
2885	.0045		12575	-.0011	
3247	-.0033		12950	.0024	
3613	.0020		13314	-.0037	
4005	-.0006		13676	.0049	
4124	-.0005		14037	-.0061	
4288	-.0009	←End of	14397	.0071	
4669	.0022	Above Ramp	14758	-.0080	
5033	-.0035	.0019	15119	.0088	
5395	.0047		15479	-.0093	
5757	-.0059		15839	.0097	Max here ~ .01
6117	.0070		16200	-.0100	
6478	-.0079		16560	.0100	
6839	.0086		16920	-.0098	
7199	-.0093		17281	.0095	
7559	.0097		17641	-.0090	
7920	-.0099		18002	.0083	
8280	.0100		18362	-.0074	
8640	-.0099		18723	.0064	
9001	.0096		19084	-.0053	
9361	-.0091		19446	.0041	
9722	.0084		19809	-.0028	
			20177	.0015	
			20321	.0006	-.0011

Second Seg. Max (above) ~ .03 Amplitude

APPENDIX A

NO RAMP # 6 (See 2 and 2A)

A = .23462000   Q = .70482000   GAMMA = .00000

Y-AXIS Analysis

PHASE	AMP		PHASE	AMP	PHASE	AMP	
0	.0100		6837	-.0090	13673	.0063	
180	.0199		7021	-.0185	13862	.0136	
361	.0099		7198	-.0095	14035	.0073	
540	.0195		7380	-.0194	14222	.0155	
722	.0096		7559	-.0099	14396	.0082	
899	.0187		7740	-.0198	14581	.0171	
1083	.0091		7920	-.0100	14757	.0089	
1259	.0175		8100	-.0199	14941	.0184	
1444	.0084		8281	-.0099	15118	.0095	
1618	.0160		8460	-.0195	15301	.0193	
1805	.0076		8642	-.0097	15479	.0098	
1978	.0142		8819	-.0188	15660	.0198	
2167	.0066		9002	-.0092	15840	.0100	
2337	.0120		9179	-.0177	16020	.0199	←2nd Seg.
2529	.0054		9363	-.0085	16201	.0100	Max ~ .1
2696	.0097		9539	-.0162	16380	.0196	
2892	.0042		9725	-.0077	16561	.0097	
3055	.0071		9898	-.0144	16739	.0189	
3260	.0028		10086	-.0067	16922	.0093	
3411	.0044		10257	-.0124	17099	.0179	
3643	.0014		10448	-.0056	17283	.0086	
3755	.0017		10617	-.0100	17459	.0165	
4175	-.0013		10812	-.0044	17645	.0078	
4266	-.0011		10975	-.0075	17818	.0147	
4510	-.0040	←End	11178	-.0030	18006	.0069	
4659	-.0026	of	11332	-.0048	18178	.0127	
4866	-.0067	Ramp	11557	-.0016	18368	.0058	
5027	-.0040	Above	11680	-.0021	18537	.0104	
5224	-.0093		12120	.0009	18731	.0046	
5391	-.0053		12161	.0009	18895	.0079	
5583	-.0117		12431	.0036	19097	.0032	
5753	-.0064		12577	.0024	19253	.0052	
5942	-.0139		12786	.0063	19472	.0018	
6115	-.0074		12946	.0038	19603	.0025	
6302	-.0157		13144	.0089	20321	-.0031	-.0017
6476	-.0083		13310	.0051			
6661	-.0173		13503	.0114	Max ~ .3 with 2nd segment		

APPENDIX A

X-RODS NO RAMP #7 (See 3 and 3A)

Quadrupole Trajectory Maxima

Enter A,Q,ETA,GAMA,I PHASE, X and/or Y

A = .23300000 Q = .70600000 GAMMA = .00000

X-AXIS Analysis

PHASE	AMP		PHASE	AMP	
0	.0100		10806	-.0043	
360	-.0099		11169	.0029	
721	.0096		11537	-.0016	
1081	-.0091		12220	.0013	
1442	.0084		12591	-.0027	
1802	-.0076		12954	.0041	
2163	.0066		13316	-.0053	
2524	-.0054		13677	.0065	
2886	.0042		14038	-.0075	
3249	-.0029		14398	.0083	
3618	.0015		14759	-.0090	
4301	-.0014		15119	.0096	
4671	.0028	←End of Ramp Above ~ .002	15480	-.0099	
5034	-.0041		15840	.0100	
5396	.0054		16200	-.0099	
5757	-.0065		16561	.0096	
6118	.0075		16921	-.0092	
6478	-.0084		17282	.0085	
6839	.0091		17642	-.0077	
7199	-.0096		18003	.0067	
7560	.0099		18364	-.0056	
7920	-.0100		18725	.0043	
8280	.0099		19088	-.0030	
8641	-.0096		19456	.0016	
9001	.0091		20139	-.0013	
9362	-.0085		20321	.0003	.0022
9722	.0076				
10083	-.0066				
10444	.0055				

Second Rod Max ~ .035

APPENDIX A

Y-RODS NO RAMP #8 (See 4 and 4A)

A = .23300000 Q = .70600000 GAMMA = .00000

Y-AXIS Analysis

PHASE	AMP	PHASE	AMP	PHASE	AMP	
0	.0100	7358	-.0029	14941	-.0197	
180	.0198	7783	.0017	15119	-.0100	
362	.0098	7857	.0016	15300	-.0199	
539	.0189	8110	.0060	15481	-.0099	
724	.0090	8259	.0039	15659	-.0192	
898	.0169	8465	.0100	15844	-.0093	
1087	.0078	8628	.0059	16018	-.0176	
1257	.0142	8823	.0136	16206	-.0082	
1451	.0062	8992	.0075	16377	-.0151	
1615	.0108	9182	.0165	16570	-.0067	
1819	.0043	9355	.0088	16736	-.0188	
1971	.0068	9541	.0186	16936	-.0049	
2204	.0021	9718	.0096	17093	-.0080	
2314	.0025	9900	.0197	17312	-.0028	
2733	-.0021	10080	.0100	17443	-.0038	
2829	-.0018	10260	.0199	18192	.0051	
3069	-.0064	10442	.0098	18335	.0035	
3220	-.0041	10619	.0191	18546	.0092	
3425	-.0104	10804	.0092	18706	.0055	
3588	-.0061	10978	.0174	18904	.0129	
3783	-.0139	11167	.0081	19071	.0072	
3952	-.0077	11337	.0148	19262	.0160	
4142	-.0167	11530	.0066	19435	.0086	
4315	-.0089	11695	.0115	19621	.0182	
4501	-.0187 ←End	11897	.0047	19797	.0095	
4678	-.0097 Above	12052	.0076	19981	.0196	
4860	-.0198 Ramp ~	12275	.0026	20159	.0100	
5040	-.0100 .037	12401	.0034	20321	.0196	.0064
5220	-.0199	12853	-.0013			
5402	-.0098	12868	-.0013			
5579	-.0190	13151	-.0055			
5764	-.0091	13297	-.0037			
5938	-.0172	13506	-.0096			
6127	-.0080	13667	-.0057			
6297	-.0145	13864	-.0132			
6491	-.0064	14032	-.0074			
6655	-.0111	14222	-.0162			
6858	-.0045	14395	-.0087			
7012	-.0072	14581	-.0184			
7239	-.0023	14757	-.0096			

APPENDIX A

ANALYSIS II

a = .233000; q = .70600

ac ramp 0° to 4320°

γ = .01

η .01

ϕ C°

Also compared with no ramp condition.

X-RAMP #1

```
Segmented Rod Transmission Analysis
Enter A and Q, DC and AC Ramp Entrances, and Exits
?.233,.706,2160,,4320,4320,
Enter Initial Phase
?0,

A = .23300000  Q = .70600000
          DC RAMP

Entrance = 2160  Exit = 4320    (Delayed

          AC RAMP

Entrance = 0  Exit = 4320

X-AXIS Analysis  1

Enter ETA and GAMMA
?.01,.01,
X-ETA = .0100  X-GAMMA = .01000 (Initial)

Initial Phase = 0
```

PHASE	AMP
1111	.0688
1228	.0661
1449	.0832
1613	.0729
1795	.0880
1995	.0675
2139	.0766
3241	-.0605
3974	.0525

Phase Distance = 4320 Phase Angle = 360 ϕ

X-ETAF = η .0226 X-GAMMAF = -.02557 γ

APPENDIX A

Y-AXIS Analysis 1A

Enter ETA and GAMMA A = 233000
?.01,.01, Q = 706000
Y-ETA = .0100 Y-GAMMA = .01000

Initial Phase = 0

PHASE	AMP
953	.0589
1026	.0584
1278	.0753
1422	.0693
1621	.0855
1803	.0706
1967	.0830
2191	.0575
2308	.0621
3452	-.0573
3553	-.0529
3801	-.1161
3922	-.1004
4159	-.2221
4282	-.1883

Phase Distance = 4320 Phase Angle = 360 ϕ

Y-ETAF η = -.1987 Y-GAMMAF γ = -.10983

APPENDIX A

SHORT X-ROD #2

Enter A,Q,ETA,GAMA,I PHASE, X and/or Y

A = .23300000 Q = .70600000 GAMMA - -.02557 Derived η and γ

X-AXIS Analysis

PHASE	AMP	
4320	.0226	
4667	-.0805	
5033	.1356	
5395	-.1881	
5756	.2369	
6117	-.2809	
6478	.3193	
6839	-.3512	
7199	.3761	
7559	-.3932	
7920	.4025	
8280	-.4036	
8641	.3965	
9001	-.3814	
9361	.3586	
9722	-.3285	
10083	.2918	
10443	-.2492	
10805	.2015	
11167	-.1499	
11531	.0954	
11908	-.0397	
12092	-.0206	
12184	-.0231	
12586	.0776	
12952	-.1327	
13315	.1854	
13676	-.2345	
14037	.2788	
14398	-.3175	
14758	.3497	
15119	-.3749	
15479	.3925	
15840	-.4022	
16001	-.0470	.4881
16001	-.0470	.4881

APPENDIX A

LONG X-ROD #3

Quadrupole Trajectory Maxima

Enter A,Q,ETA,GAMA,I PHASE, X and/or Y
?.233,.706,.0226,-.02557,X←<←,X

A = .23300000   Q = .70600000   GAMMA = -.02557

X-AXIS Analysis

PHASE	AMP	PHASE	AMP	
0	.0226	8266	.0776	
347	-.0805	8632	-.1327	
713	.1356	8995	.1854	
1075	-.1881	9356	-.2345	
1436	.2369	9717	.2788	
1797	-.2809	10078	-.3175	
2158	.3193	10438	.3497	
2519	-.3512	10799	-.3749	
2879	.3761	11159	.3925	
3239	-.3932	11520	-.4022	
3600	.4025	11880	.4037	←End of short rod
3960	-.4036	12240	-.3971	
4321	.3965	12601	.3824	
4681	-.3814	12961	-.3599	
5041	.3586	13322	.3303	
5402	-.3285	13682	-.2939	
5763	.2918	14043	.2515	
6123	-.2492	14404	-.2041	
6485	.2015	14766	.1527	
6847	-.1499	15131	-.0983	
7211	.0954	15506	.0426	
7588	-.0397	15707	.0199	
7772	-.0206	15772	.0207	
7864	-.0231	16001	-.0164	-.0478
		16001	-.0164	-.0478

APPENDIX A

Quadrupole Trajectory Maxima #4

Enter A,Q,ETA,GAMA,I PHASE, X and/or Y
?.233,.706,.0226,-.02557,4320,X

A = .23300000 Q = .70600000 GAMMA = -.02557

X-AXIS Analysis

PHASE	AMP		PHASE	AMP	
4320	.0226		12586	.0776	
4667	-.0805		12952	-.1327	
5033	.1356		13315	.1854	
5395	-.1881		13676	-.2345	(Off-set of phase
5756	.2369		14037	.2788	on long rod)
6117	-.2809		14398	-.3175	
6478	.3193		14758	.3497	
6839	-.3512		15119	-.3749	
7199	.3761		15479	.3925	
7559	-.3932	See	15840	-.4022	
7920	.4025	Long	16200	.4037	
8280	-.4036	X-Rod	16560	-.3971	
8641	.3965	Above	16921	.3824	
9001	-.3814		17281	-.3599	
9361	.3586		17642	.3303	
9722	.3285		18002	-.2939	
10083	.2918	-.0021	18363	.2515	
10443	-.2492		18724	-.2041	
10805	.2015		19086	.1527	
11167	-.1499		19451	-.0983	
11531	.0954		19826	.0426	
11908	-.0397		20027	.0199	
12092	-.0206		20092	.0207	
12184	-.0231		20321	-.0164	-.0478
			20321	-.0164	-.0478

APPENDIX A

NO RAMP COMPARISON #5

Quadrupole Trajectory Maxima

Enter A,Q,ETA,GAMA,I PHASE, X and/or Y
?.233,.706,.01,.01,0,XY

A = .23300000 Q = .70600000 GAMMA = .01000

X-AXIS Analysis

PHASE	AMP		PHASE	AMP	
0	.0100		10438	-.1264	
42	.0111		10799	.1386	
170	.0084		11159	-.1480	
327	.0134		11519	.1544	
708	-.0351		11880	-.1577	Max here is ~1/3
1073	.0565		12240	.1577	max of second
1435	-.0768		12601	-.1546	segment
1797	.0956		12961	.1484	
2157	-.1125		13321	-.1391	
2518	.1271		13682	.1271	
2879	-.1392		14043	-.1124	
3239	.1484		14403	.0955	
3599	-.1547		14765	0767	
3960	.1578		15127	.0563	
4320	-.1577		15492	-.0349	
4681	.1544	←End of	15874	.0)32	
5041	-.1480	Above	16029	.0084	
5401	.1386	Ramp	16159	.0112	
5762	-.1264	A ~ .05	16547	-.0328	
6123	.1116	@ 3974°	16913	.0543	
6484	-.0946		17275	-.0747	
6845	.0757		17636	.0937	
7207	-.0552		17997	-.1109	
7572	.0338		18358	.1257	
7957	-.0121		18719	-.1381	
8099	-.0084		19079	.1476	
8243	-.0123		19439	-.1542	
8628	.0339		19800	.1576	
8993	-.0554		20160	-.1578	
9355	.0758		20321	-.0196	.1898
9716	-.0947				
10077	.1117				

APPENDIX A

Quadrupole Trajectory Maxima

Enter A,Q,ETA,GAMA,I PHASE, X and/or Y
?.233,.706,-.1987,-.10983,4320,Y

A = .23300000 Q = .70600000 GAMMA = -.10983

Y-AXIS Analysis #2A

PHASE	AMP		
4320	-.1987		
4506	-.5067		
4667	-.3016		See Y-Rod Above
4864	-.7046		
5032	-.3944		
5222	-.8678		
5395	-.4669		
5581	-.9883		
5757	-.5159		
5941	-1.0599		
20321	-1.0599	-.0478	
23021	-1.0599	-.0478	

Y-ROD (LONG) Calculated Values From Above

Quadrupole Trajectory Maxima

Enter A,Q,ETA,GAMA,I PHASE, X and/or Y
?.233,.706,-.1987,-.10983,0,Y

A = .23300000 Q = .70600000 GAMMA = -.10983

Y-AXIS Analysis #3A

PHASE	AMP	
0	-.1987	
186	-.5067	
347	-.3016	
544	-.7046	
712	-.3944	
902	-.8678	
1075	-.4669	
1261	-.9883	
1437	-.5159	
1621	-1.0599	
16001	-1.0599	-.0478
16001	-1.0599	-.0478

APPENDIX A

Y-ROD NO RAMP #5A

A = .23300000 Q = .70600000 GAMMA = .01000

Y-AXIS Analysis

PHASE	AMP	PHASE	AMP	PHASE	AMP	
0	.0100	5943	-.0738	12779	.0902	
189	.0301	6112	-.0354	12964	.0434	
340	.0194	6302	-.0774	13138	.0824	
545	.0489	6475	-.0414	13326	.0384	
708	.0285	6661	-.0871	13497	.0706	
903	.0653	6838	-.0452	13690	.0315	
1073	.0361	7020	-.0925	13856	.0552	
1262	.0785	7200	-.0468	14056	.0229	
1435	.0419	7380	-.0934	14213	.0372	
1621	.0878	7562	-.0461	14432	.0129	
1798	.0455	7739	-.0896	14563	.0175	
1980	.0928	7924	-.0430	15312	-.0243	
2160	.0469	8098	-.0814	15456	-.0164	
2340	.0932	8287	-.0378	15666	-.0436	
2522	.0459	8457	-.0692	15826	-.0260	
2699	.0890	8650	-.0307	16024	-.0608	
2884	.0426	8815	-.0536	16191	-.0340	
3058	.0804	9017	-.0220	16382	-.0750	
3247	.0372	9172	-.0353	16555	-.0404	
3417	.0678	9396	-.0118	16741	-.0855	
3611	.0299	9521	-.0155	16917	-.0447	
3775	.0519	9964	.0063	17101	-.0918	
3978	.0210	0007	.0063	17279	-.0467	
4132	.0334	10271	.0262	17560	-.0936	
End of above ramp.		10417	.0174	17641	-.0464	
Max ~0.22 with ramp		10626	.0454	17819	-.0907	
(hits rods with ramp)		10787	.0268	18003	-.0438	
4360	.0108	10984	.0623	18178	-.0834	
4477	.0135	11152	.0347	18366	-.0390	
4901	-.0081	11342	.0762	18537	-.0719	
4979	-.0076	11515	.0409	18730	-.0323	
5230	-.0282	11701	.0863	18896	-.0569	
5379	-.0184	11877	.0450	19095	-.0238	
5585	-.0472	12061	.0922	19252	-.0391	
5748	-.0277	12239	.0468	19469	-.0140	
		12420	.0935	19605	-.0194	
		12601	.0463	20321	.0213	.0120

APPENDIX A

ANALYSIS III

$a = .2346200$; $q = .7048200$

ac ramp 0° to 4320°

dc ramp 2160° to 4320° and 2160° to 6480°

$\gamma = 0$; .01

$\eta = .01$

$\phi = 0°$; 90°

Compare with Analysis I

```
Segmented Rod Transmission Analysis
Enter A and Q, DC and AC Ramp Entrances, and Exits
?.23462,.70482,2160,4320++++,4320,4320,
Enter Initial Phase
?0,
A = .23462000  Q = .70482000
           DC RAMP
Entrance = 2160  Exit = 4320
           AC RAMP
Entrance = 0  Exit = 4320
X-AXIS ANALYSIS - DC DELAYED #1
Enter ETA and GAMMA
?.01,,
X-ETA = .0100  X-GAMMA = .00000 Initial
Initial Phase = 0
```

PHASE	AMP	PHASE	AMP
134	.0100	1422	.0099
358	.0104	1649	.0075
530	.0100	1768	.0079
715	.0107	2897	-.0053
900	.0097	3068	-.0040
1070	.0107	3209	-.0048
1271	.0090	3949	.0053

```
Phase Distance = 4320  Phase Angle = 360
X-ETAF = -.0019  X-GAMMAF = -.00230
```

APPENDIX A

Y-AXIS ANALYSIS #1A

Enter ETA and GAMMA
?.01,,
Y-ETA = .0100 Y-GAMMA = .00000
Initial Phase = 0

PHASE	AMP
134	.0100
362	.0096
525	.0100
726	.0091
886	.0097
1093	.0084
1241	.0090
1467	.0071
1589	.0075
1867	.0048
1912	.0048
2769	-.0040
2802	-.0040
3084	-.0083
3204	-.0074
3438	-.0140
3568	-.0119
3798	-.0236
3925	-.0199
4159	-.0429
4282	-.0362

Phase Distance = 4320 Phase Angle = 360

Y-ETAF = -.0382 Y-GAMMAF = .02092

APPENDIX A

```
SEGMENTED ROD TRANSMISSION ANALYSIS
Enter A and Q, DC and AC Ramp Entrances, and Exits
?.23462,.70482,2160,,4320,4320,
Enter Initial Phase
?0,
A = .23462000  Q = .70482000

          DC RAMP

Entrance = 2160  Exit - 4320

          AC RAMP

Entrance = 0  Exit - 4320

X-AXIS ANALYSIS #2
Enter ETA and GAMMA
?.01,.01,
X-ETA = .0100  X-GAMMA - .01000   Initial
Initial Phase = 0

PHASE         AMP

 1111        .0688
 1228        .0660
 1449        .0831
 1613        .0729
 1795        .0880
 1995        .0676
 2139        .0767
 3241       -.0605
 3974        .0525

Phase Distance = 4320  Phase Angle - 360

X-ETAF = .0224  X-GAMMAF = -.02565
```

APPENDIX A

Y-AXIS ANALYSIS #2A
Enter ETA and GAMMA
?.01,.01,

Y-ETA = .0100 Y-GAMMA = .01000

Initial Phase = 0

PHASE	AMP
953	.0589
1026	.0584
1278	.0752
1422	.0693
1621	.0855
1803	.0706
1968	.0831
2191	.0576
2308	.0623
3453	-.0562
3552	-.0521
3802	-.1150
3921	-.0999
4160	-.2221
4281	-.1891

Phase Distance = 4320 Phase Angle = 360

Y-ETAF = -.1998 Y-GAMMAF = -.11207

APPENDIX A

SEGMENTED ROD TRANSMISSION ANALYSIS

Enter A and Q, DC and AC Ramp Entrances, and Exits
?.23462,.70482,2160,,4320,4320,
Enter Initial Phase
?90,

A = .23462000 Q = .70482000

DC RAMP

Entrance = 2160 Exit = 4320

AC RAMP

Entrance = 0 Exit - 4320

X-AXIS ANALYSIS #3

Enter ETA and GAMMA
?.01,,

X-ETA = .0100 X-GAMMA = .00000 Initial ϕ = 90°
Initial Phase = 90

PHASE	AMP
257	.0102
445	.0098
621	.0104
812	.0095
978	.0102
1182	.0088
1332	.0095
1558	.0073
1679	.0078
1973	.0048
1987	.0048
2817	-.0045
2960	-.0038
3130	-.0050
3869	.0052

Phase Distance = 4320 Phase Angle = 360

X-ETAF = -.0010 X-GAMMAF = -.00194

APPENDIX A

Y-AXIS ANALYSIS #3A

Enter ETA and GAMMA
?.01,,

Y-ETA = .0100 Y-GAMMA = .00000

Initial Phase = 90

PHASE	AMP
258	.0098
441	.0102
629	.0095
800	.0102
997	.0091
1156	.0099
1368	.0081
1507	.0087
1752	.0061
1847	.0064
3001	-.0071
3108	-.0065
3349	-.0126
3477	-.0109
3708	-.0213
3836	-.0180
4068	-.0380
4193	-.0321

Phase Distance = 4320 Phase Angle = 360

Y-ETAF = -.0525 Y-GAMMAF = -.05665

APPENDIX A

```
SEGMENTED ROD TRANSMISSION ANALYSIS
Enter A and Q, DC and AC Ramp Entrances, and Exits
?.23462,.70482,2160,,4320,4320,
Enter Initial Phase
?90,
A = .23462000 Q =  .70482000

     DC RAMP

Entrance  = 2160 Exit = 4320

     AC RAMP

Entrance =     0 Exit = 4320

X-AXIS ANALYSIS #4
Enter ETA and GAMMA
?.01,.01,
X-ETA =  .0100 X-GAMMA =  .01000
Initial Phase  =  90

PHASE          AMP

1030          .0636
1129          .0621
1363          .0790
1518          .0711
1708          .0868
1899          .0693
2054          .0801
2295          .0516
2381          .0534
3163         -.0557
3356         -.0375
3465         -.0413
3906          .0396
4042          .0322
4200          .0436

Phase Distance  =  4320 Phase Angle = 360

X-ETAF  =  .0224 X-GAMMAF = -.05492
```

APPENDIX A

Y-AXIS ANALYSIS #4A
Enter ETA and GAMMA
?.01,.01,
Y-ETA = .0100 Y-GAMMA = .01000
Initial Phase = 90

PHASE	AMP
1194	.0725
1325	.0683
1535	.0851
1708	.0726
1881	.0866
2092	.0635
2224	.0704
2506	.0382
2540	.0383
3371	-.0460
3454	-.0440
3713	-.0993
3830	-.0871
4070	-.1916
4191	-.1636

Phase Distance = 4320 Phase Angle = 360

Y-ETAF = -.2699 Y-GAMMAF = -.29306

APPENDIX A

SEGMENTED ROD TRANSMISSION ANALYSIS

Enter A and Q, DC and AC Ramp Entrances, and Exits
?.23462,.70482,2160,43++,6480,4320,
Enter Initial Phase
?0,

A = .23462000 Q = .70482000

DC RAMP

Entrance = 2160 Exit = 6480

AC RAMP

Entrance = 0 Exit = 4320

X-AXIS Analysis #5
Enter ETA and GAMMA
?.01,,

X-ETA = .0100 X-GAMMA = .00000
Initial Phase = 0

PHASE	AMP	PHASE	AMP
134	.0100	3973	.0055
358	.0104	4163	.0034
530	.0100	4282	.0039
715	.0107	4705	-.0046
900	.0097	4863	-.0034
1070	.0107	5011	-.0045
1271	.0090	5428	.0044
1422	.0099	5584	.0032
1649	.0075	5728	.0042
1768	.0079	6141	-.0049
2903	-.0054	6336	-.0029
3049	-.0045	6422	-.0031
3226	-.0061		

Phase Distance = 6480 Phase Angle = 360

X-ETAF = -.0028 X-GAMMAF = .00240

APPENDIX A

Y-AXIS ANALYSIS #5A

Enter ETA and GAMMA
?.01,,

Y-ETA = .0100 Y-GAMMA = .00000
Initial Phase = 0

PHASE	AMP
134	.0100
362	.0096
525	.0100
726	.0100
886	.0097
1093	.0084
1241	.0090
1467	.0071
1589	.0075
1867	.0048
1912	.0048
2757	-.0039
2818	-.0039
3075	-.0074
3223	-.0060
3422	-.0094
3601	-.0065
3774	-.0093
3979	-.0053
4124	-.0068
4906	.0034
4982	.0033
5236	.0083
5373	.0066
5592	.0137
5736	.0106
5954	.0216
6091	.0171
6317	.0368
6445	.0305

Phase Distance = 6480 Phase Angle = 360

Y-ETAF = .0319 Y-GAMMAF = .01651

APPENDIX A

```
SEGMENTED ROD TRANSMISSION ANALYSIS
Enter A and Q, DC and AC Ramp Entrances, and Exits
?.23462.,70482,2160,,6480,4320,
Enter Initial Phase
?0,
A = .23462000 Q = .70482000

     DC RAMP

Entrance = 2160 Exit = 6480

     AC RAMP

Entrance =    0 Exit = 4320

X-AXIS ANALYSIS #6
Enter ETA and GAMMA
?.01,.01,
X-ETA = .0100 X-GAMMA = .01000
Initial Phase = 0
```

PHASE	AMP
1111	.0638
1228	.0660
1449	.0831
1613	.0729
1795	.0880
1995	.0676
2139	.07[illegible]
2411	.044[illegible]
2446	.0447
3251	-.0600
3435	-.0[illegible]13
3569	-.0492
4313	.0602
5037	-.0603
5755	.0589
6468	-.0545

```
Phase Distance = 6480 Phase Angle = 360

X-ETAF = -.0541 X-GAMMAF = .01076
```

APPENDIX A

Y-AXIS ANALYSIS #6A
Enter ETA and GAMMA
?.01,.01,
Y-ETA = .0100 Y-GAMMA = .01000
Initial Phase = 0

PHASE	AMP
953	.0589
1026	.0584
1278	.0752
1422	.0693
1621	.0855
1803	.0706
1968	.0831
2191	.0576
2307	.0622
3438	-.0670
3578	-.0550
3784	-.0949
3957	-.0649
4136	-.0996
4336	-.0556
4487	-.0749
4735	-.0305
4816	-.0321
5602	.0682
5724	.0578
5957	.1307
6088	.1069
6318	.2379
6444	.1985

Phase Distance = 6480 Phase Angle = 360

Y-ETAF = .2085 Y-GAMMAF = .11096

APPENDIX A

SEGMENTED ROD TRANSMISSION ANALYSIS

Enter A and Q, DC and AC Ramp Entrances, and Exits
?.23462,.70482,2160,,6480,4320,
Enter Initial Phase
?90,

A = .23462000 Q = .70482000

DC RAMP

Entrance = 2160 Exit = 6480

AC RAMP

Entrance = 0 Exit - 4320

X-AXIS ANALYSIS #7

Enter ETA and GAMMA
?.01,,
X-ETA = .0100 X-GAMMA = .00000
Initial Phase = 90

PHASE	AMP	PHASE	AMP
257	.0102	3142	-.0060
445	.0098	3895	.0044
621	.0104	4045	.0034
812	.0095	4208	.0047
978	.0102	4639	-.0032
1182	.0088	4735	-.0029
1332	.0095	4935	-.0051
1558	.0073	5371	.0028
1679	.0078	5445	.0027
1973	.0048	5654	.0049
1987	.0048	6073	-.0033
2822	-.0046	6192	-.0028
2946	-.0041	6364	-.0042

Phase Distance = 6480 Phase Angle = 360

X-ETAF = -.0023 X-GAMMAF = .00520

APPENDIX A

Y-AXIS ANALYSIS #7A

Enter ETA and GAMMA
?.01,,
Y-ETA = .0100 Y-GAMMA = .00000
Initial Phase = 90

PHASE	AMP
258	.0098
441	.0102
629	.0095
800	.0102
997	.0091
1156	.0099
1368	.0081
1507	.0087
1752	.0061
1847	.0064
2993	-.0066
3124	-.0057
3336	-.0095
3505	-.0069
3687	-.0103
3881	-.0063
4038	-.0086
4272	-.0039
4376	-.0044
5151	.0071
5278	.0059
5503	.0128
5645	.0099
5863	.0203
6002	.0160
6226	.0340
6357	.0279

Phase Distance = 6480 Phase Angle = 360

Y-ETAF = .0449 Y-GAMMAF = .04813

APPENDIX A

```
SEGMENTED ROD TRANSMISSION ANALYSIS
Enter A and Q, DC and AC Ramp Entrances, and Exits
?.23462,.70482,2160,,6480,4320,
Enter Initial Phase
?90,
A = .23462000 Q = .70482000

     DC RAMP

Entrance = 2160 Exit = 6480

     AC RAMP

Entrance =    0 Exit = 4320

X-AXIS ANALYSIS #8
Enter ETA and GAMMA
?.01,.01,
X-ETA = .0100 X-GAMMA = .01000
Initial Phase = 90

PHASE           AMP

1030           .0636
1129           .0621
1363           .0790
1518           .0711
1708           .0868
1899           .0693
2054           .0801
2294           .0517
2383           .0537
3173          -.0521
3322          -.0419
3493          -.0575
4233           .0596
4958          -.0562
5678           .0557
6391          -.0568

Phase Distance = 6480 Phase Angle = 360

X-ETAF = -.0418 X-GAMMAF = .05201
```

APPENDIX A

Y-AXIS ANALYSIS #8A
Enter ETA and GAMMA
?.01,.01,
Y-ETA = .0100 Y-GAMMA = .01000
Initial Phase = 90

PHASE	AMP
1194	.0725
1325	.0683
1535	.0851
1708	.0726
1881	.0866
2092	.0635
2224	.0704
3355	-.0585
3480	-.0507
3697	-.0912
3863	-.0652
4048	-.1027
4241	-.0608
4400	-.0854
4632	-.0382
4739	-.0429
5515	.0609
5631	.0526
5867	.1212
5998	.0989
6227	.2185
6355	.1809

Phase Distance = 6480 Phase Angle = 360

Y-ETAF = .2941 Y-GAMMA = .31753

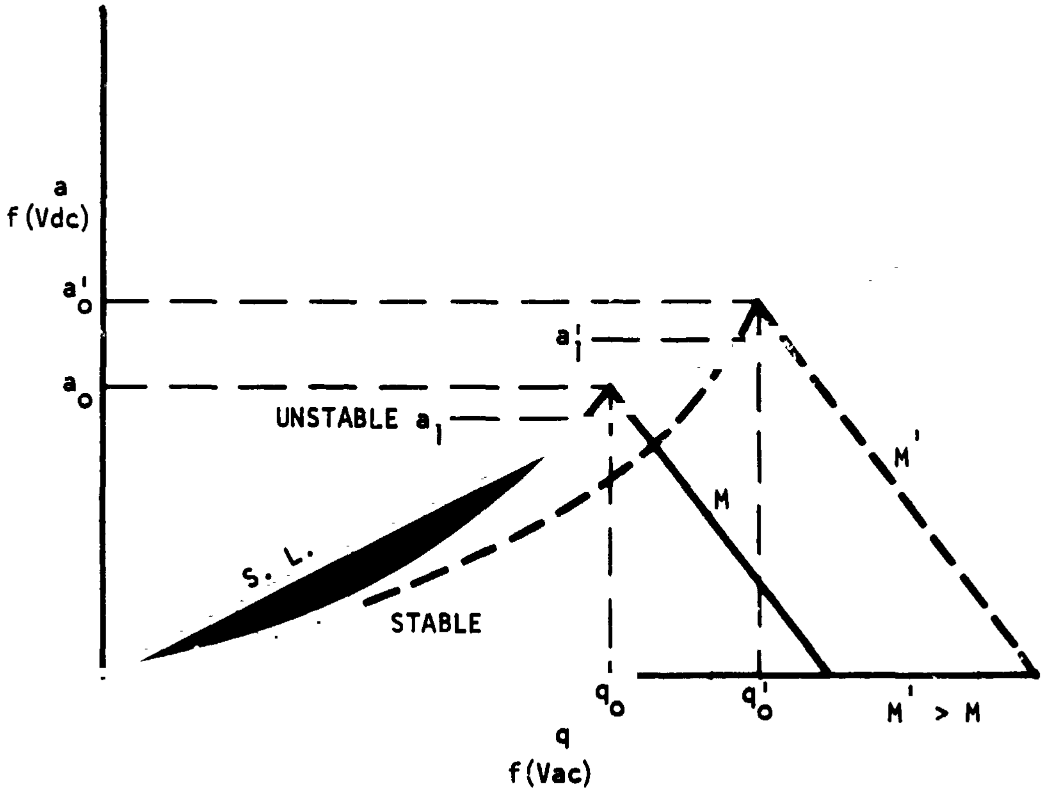

FIGURE 1. Typical Scan Line

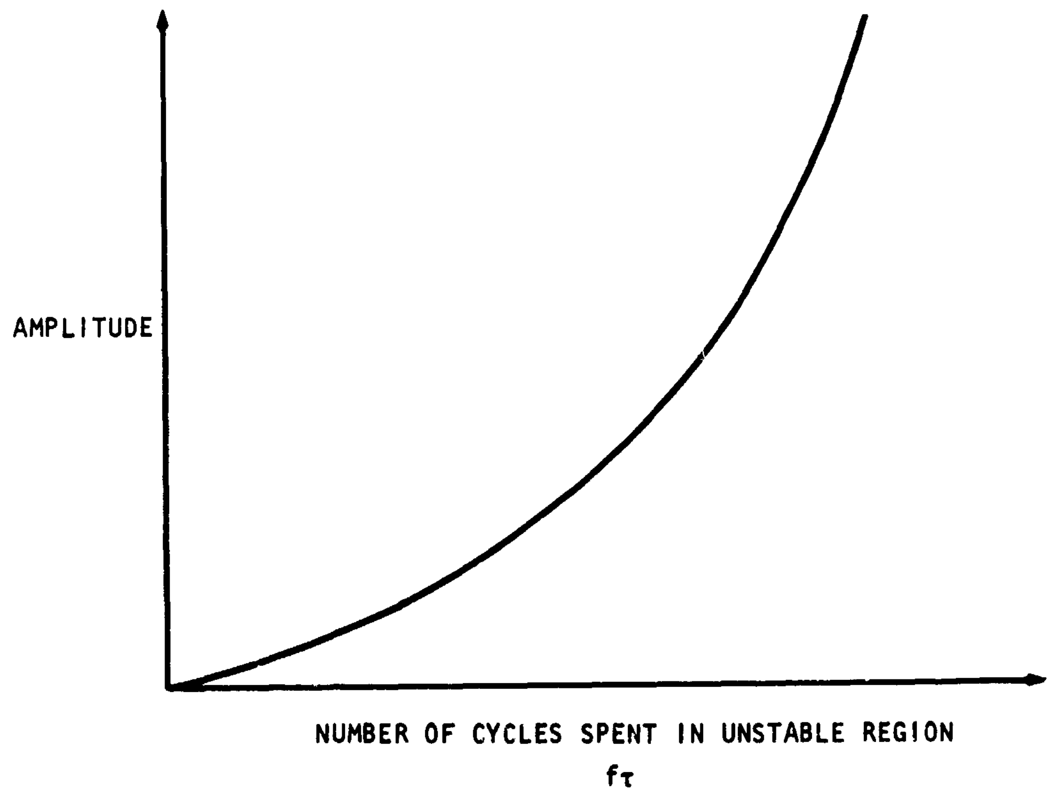

FIGURE 2. Amplitude Grcwth vs Time Spent by Ion in Unstable Region

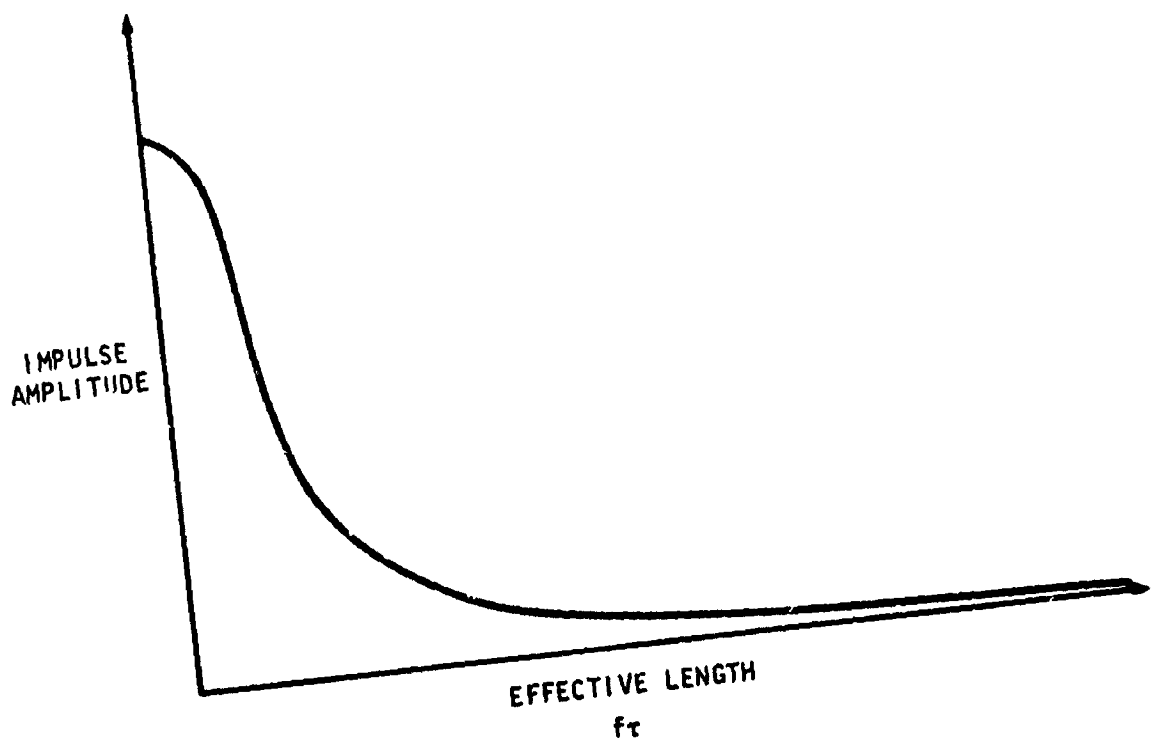

FIGURE 3. Ion Impulse vs Length of Fringe Field

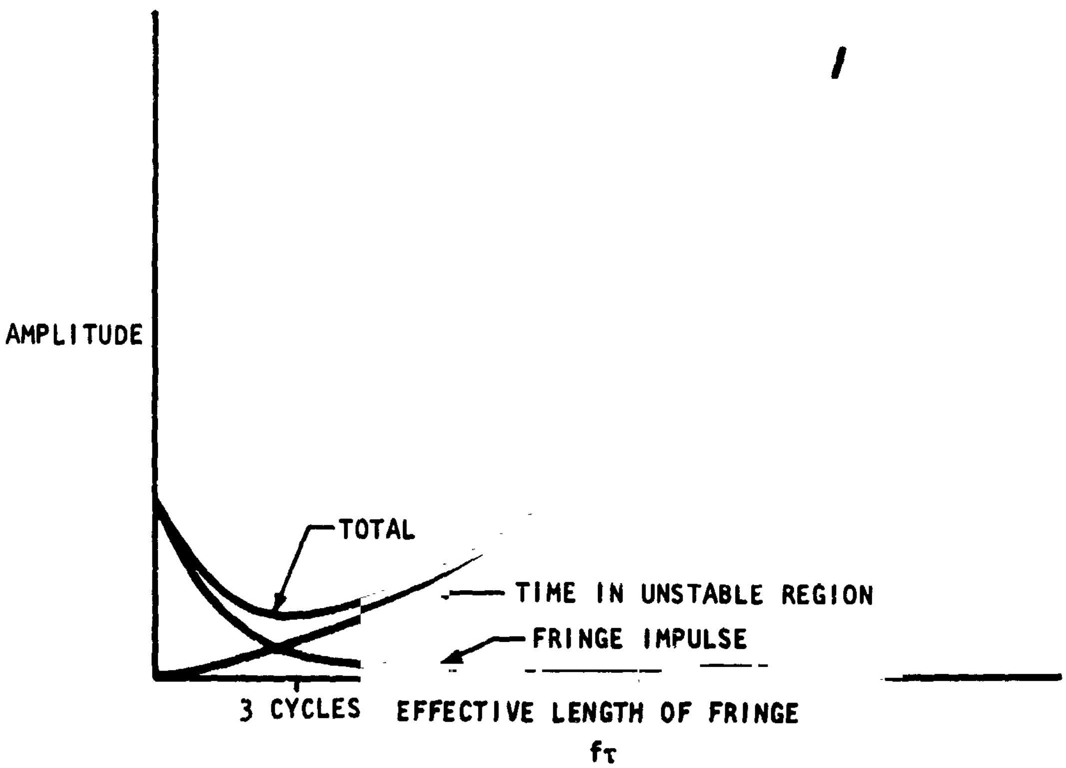

FIGURE 4. Ion Amplitude for a Given Fringe Field Length

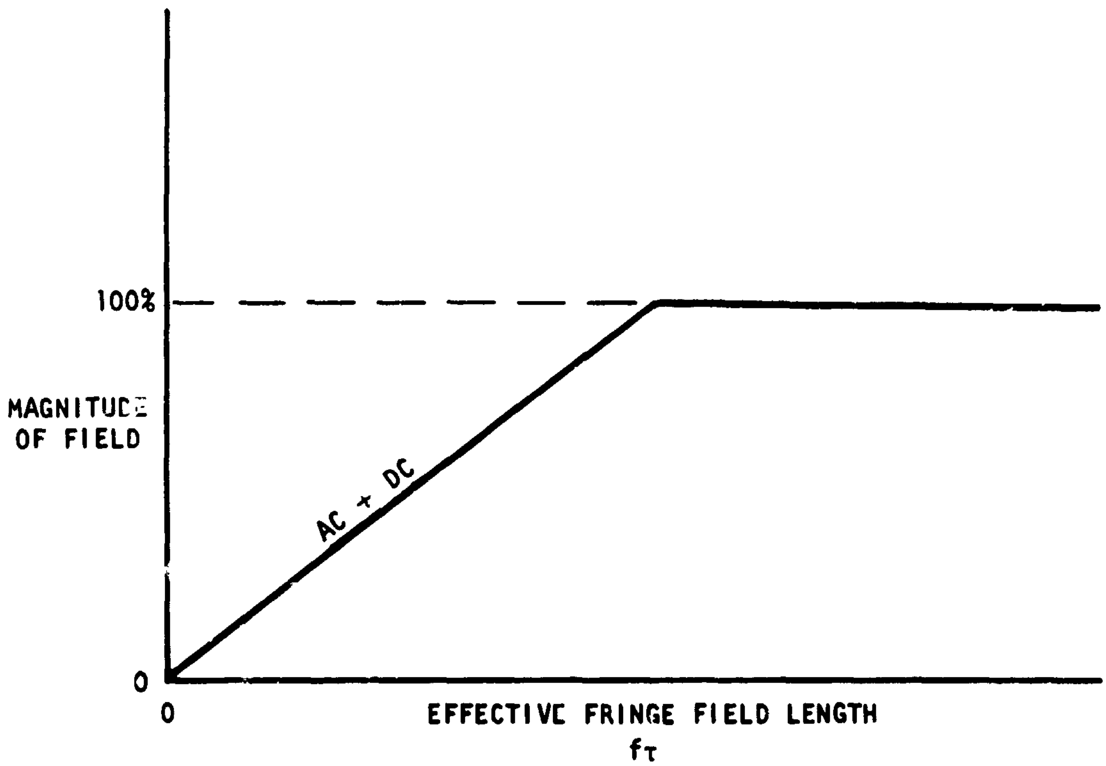

FIGURE 5. Fringe Field Ramp

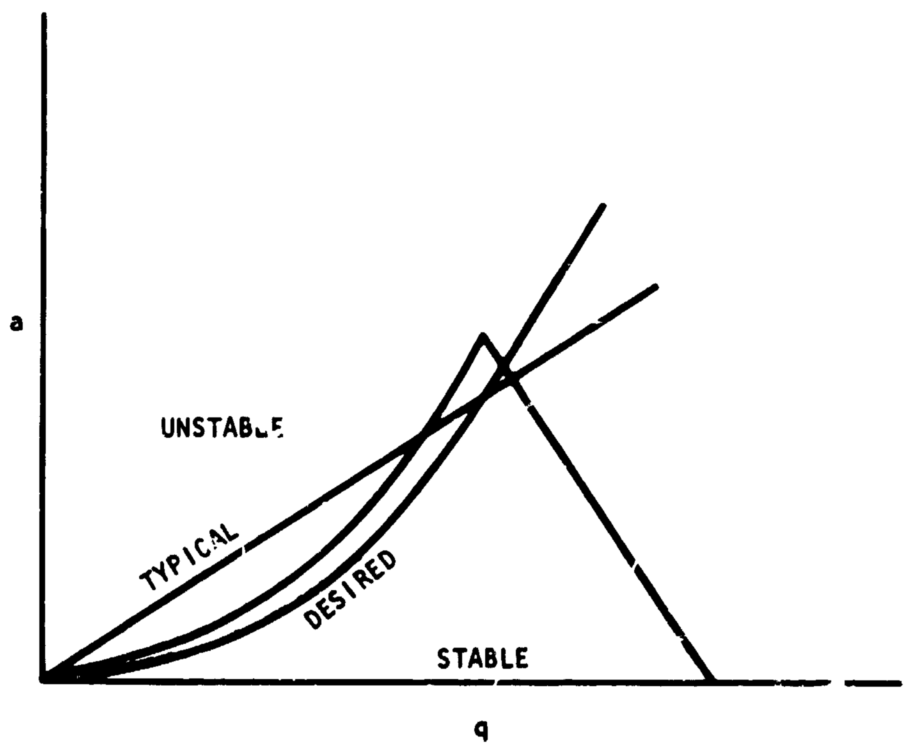

FIGURE 6. Typical vs Desired Scan Line

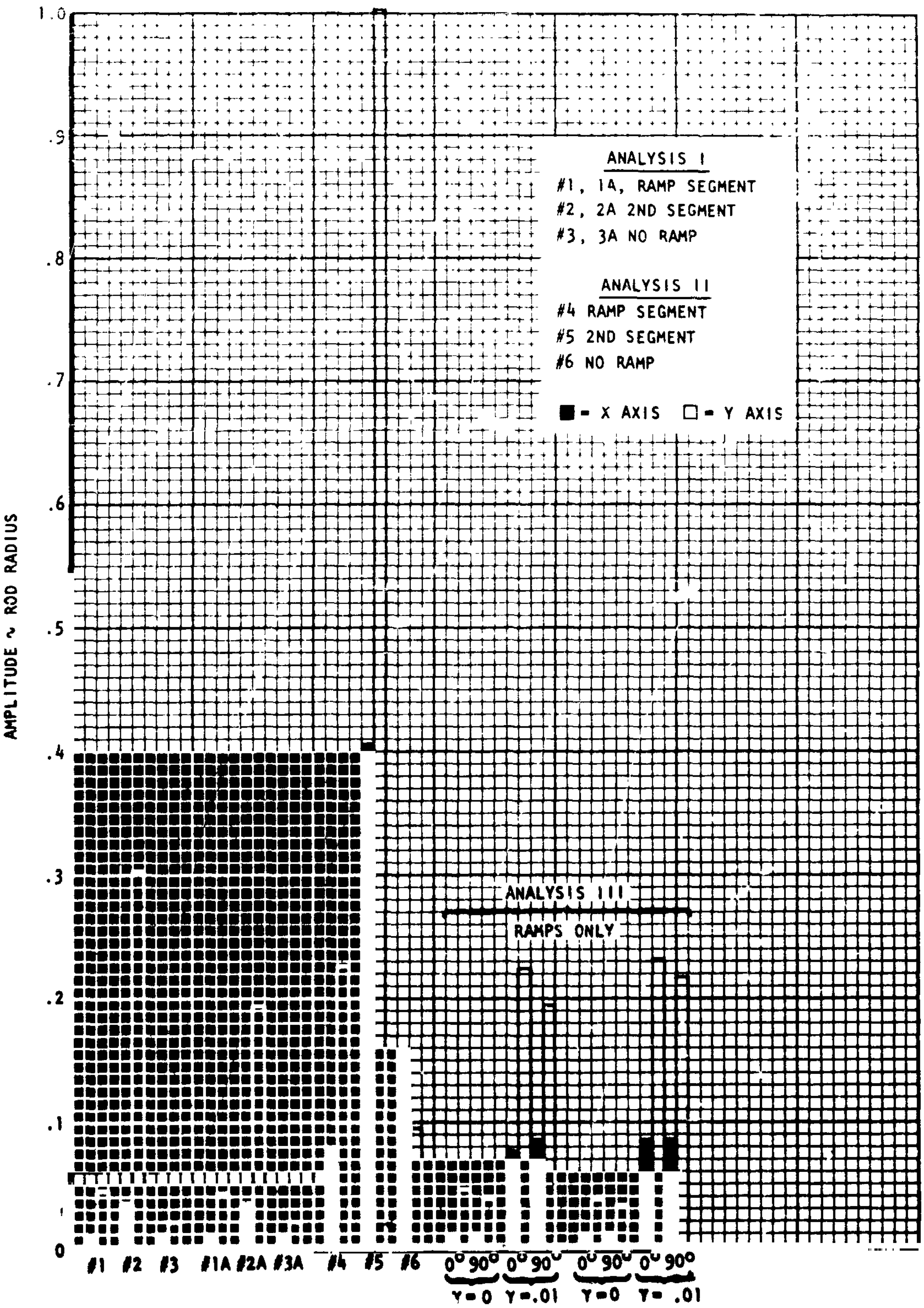

FIGURE 7. Summary of Appendix A Amplitude